MegaWatt Proton Beams for Particle Physics at Fermilab

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P5 Meeting/BNL

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Message

- The Fermilab accelerator complex can be upgraded to establish LBNE as the leading long-baseline program in the world, with >1 MW at startup (2025)
- The Proton Improvement Plan-II (PIP-II) is a complete, integrated, cost effective concept, that meets this goal while
  - leveraging U.S. investment in superconducting rf,
  - attracting international partners,
  - providing a platform for the long-term future
- PIP-II retains flexibility to eventually realize the full potential of the Fermilab complex
  - LBNE >2 MW
  - Mu2e sensitivity x10
  - MW-class, high duty factor beams for rare processes experiments
- We look forward to a positive recommendation from P5, and are in a position to move forward expeditiously.

Outline

- Program Goals
- Proton Improvement Plan
- Proton Improvement Plan-II
  - Goals
  - Strategy
  - Description of PIP-II
  - Cost Estimate
  - Platform for the Future

Program Goals

Our goal is to construct & operate the foremost facility in the world for particle physics utilizing intense beams.

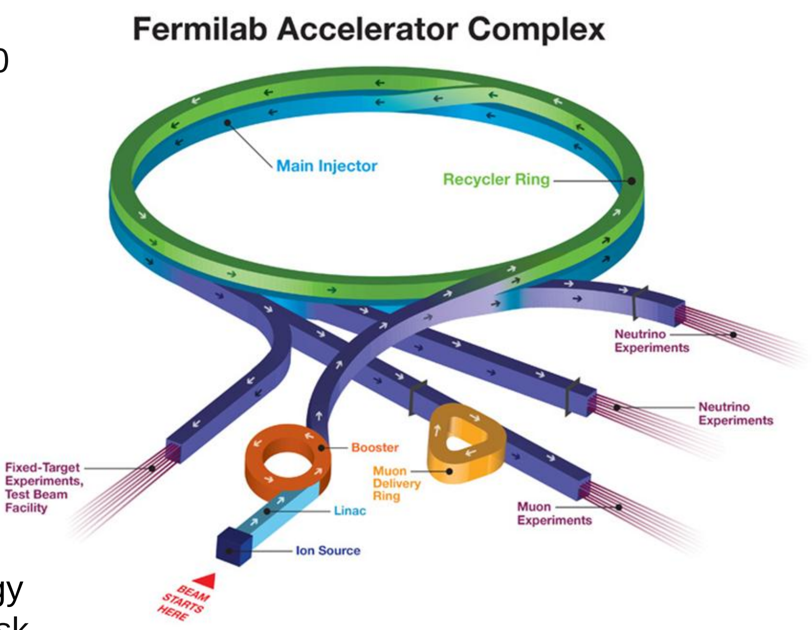
- Neutrinos
  - MINOS+, NOvA @700 kW (now)
  - LBNE @ >1 MW (2025)
  - LBNE @ >2 MW (>2030)
  - Short baseline neutrinos
- Muons
  - Muon g-2 @ 17 kW (2017)
  - Mu2e @ 8 kW (2020)
  - Mu2e @ 100 kW (>2023)
- Longer term opportunities

$\Rightarrow$ ***This will require more protons!***

Fermilab Accelerator Facts of Life

Every proton delivered to a target at Fermilab must be accelerated through the (40-year-old) Linac and Booster

- Linac
  - 2×10^{13} protons (35 mA x 100 μsec) to 400 MeV @ 15 Hz
  - Drift Tube section represents a significant operational risk
    - Many components either no longer available, or available from a single vendor operating in a minimal market
- Booster
  - 4.2×10^{12} protons to 8 GeV @ 7.5 Hz
  - Magnets cycle at 15 Hz
    - Beam cycle rate limited by rf system
  - Pulse intensity limited by space-charge at injection
    - Strongly dependent on injection energy
  - Booster represents a modest operational risk



$\Rightarrow$ ***Booster injection is the primary intensity bottleneck***

Proton Improvement Plan (2011 - 2018)

The Proton Improvement Plan supports NOvA, g-2, Mu2e, and short-baseline neutrino goals by doubling the Booster beam repetition rate to 15 Hz, while addressing reliability concerns

- Goals
  - 4.2×10^{12} protons per pulse at 15 Hz (2.2E17/hour)
  - Linac/Booster availability > 85%
  - Residual activation at acceptable levels
  - Useful operating life through 2025
- Scope
  - Increase Booster beam rep rate to 15 Hz
    - RF upgrades/refurbish
  - Replace components with high availability risk
    - DTL rf $\Rightarrow$200 MHz klystrons/modulators
    - Additional Booster rf cavities
  - Double proton flux while maintaining current levels of activation
    - RFQ, dampers, collimators/absorbers

$\Rightarrow$ ***700 kW to NOvA at 120 GeV, concurrent with 8 GeV program***

Proton Improvement Plan-II Goals

Proton Improvement Plan-II supports longer term physics research goals by providing increased beam power to LBNE while providing a platform for the future

- Design Criteria
  - Deliver 1.2 MW of proton beam power from the Main Injector to the LBNE target at 120 GeV, with power approaching 1 MW at energies down to 60 GeV, at the start of LBNE operations
  - Continue support for the current 8 GeV program, including Mu2e, Muon g-2, and the suite of short-baseline neutrino experiments; provide upgrade path for Mu2e
  - Provide a platform for eventual extension of beam power to LBNE to >2 MW
  - Provide a platform for extension of capability to high duty factor/higher beam power operations

Proton Improvement Plan-II Strategy

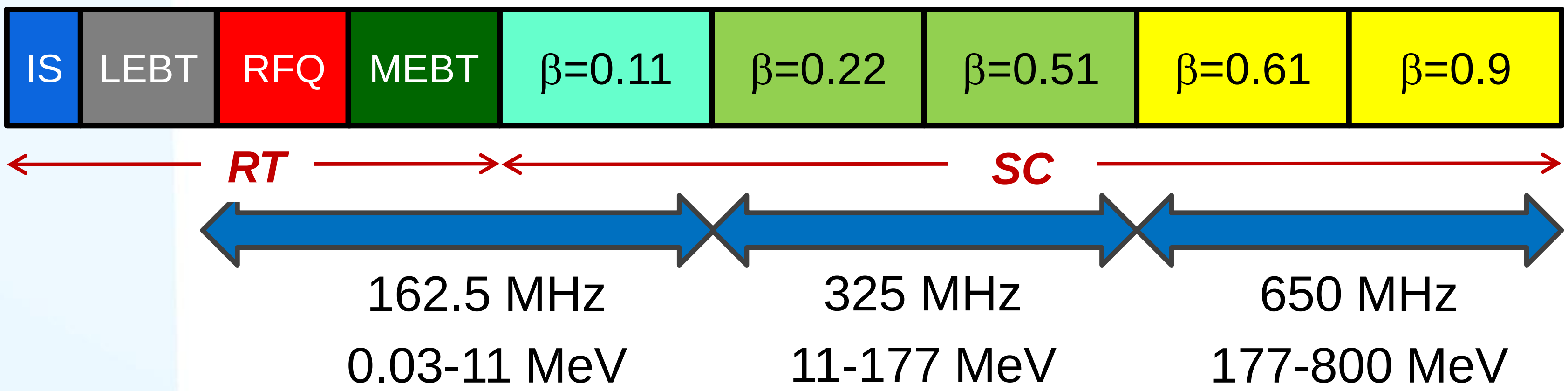
- Increase Booster/Recycler/Main Injector per pulse intensity by ~50%.
  - Requires increasing the Booster injection energy
- Select 800 MeV as preferred Booster injection energy
  - 30% reduction in space-charge tune shift w/ 50% increase in beam intensity
  - Provides margin for lower beam loss at higher intensities
- Modest modifications to Booster/Recycler/Main Injector
  - To accommodate higher intensities and higher Booster injection energy

⇒ ***Cost effective solution:***
800 MeV superconducting pulsed linac, extendible to support >2 MW operations to LBNE and upgradable to continuous wave (CW) operations
  - Builds on significant existing infrastructure
  - Capitalizes on major investment in superconducting rf technologies
  - Eliminates significant operational risks inherent in existing linac
  - Siting consistent with eventual replacement of the Booster as the source of protons for injection into Main Injector

Proton Improvement Plan-II Performance Goals

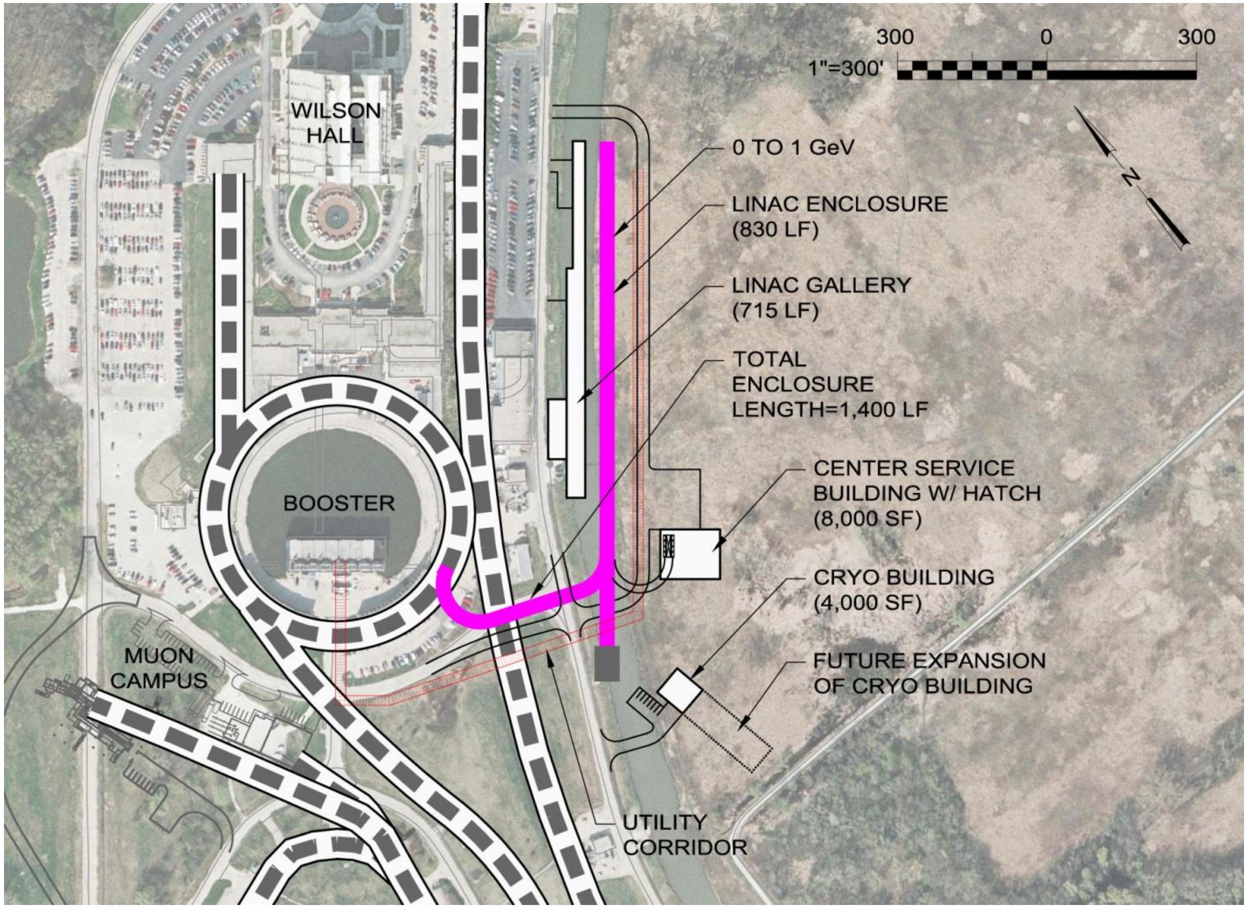
Performance Parameter	PIP-II	
Linac Beam Energy	800	MeV
Linac Beam Current	2	mA
Linac Beam Pulse Length	0.6	msec
Linac Pulse Repetition Rate	15	Hz
Linac Beam Power Capability (10-15% DF)	~200	kW
Mu2e Upgrade Potential (800 MeV)	>100	kW
Booster Protons per Pulse	6.4×10^{12}	
Booster Pulse Repetition Rate	15	Hz
Booster Beam Power @ 8 GeV	120	kW
Beam Power to 8 GeV Program (max)	40	kW
Main Injector Protons per Pulse	7.5×10^{13}	
Main Injector Cycle Time @ 120 GeV	1.2	sec
Main Injector Cycle Time @ 80 GeV	0.8	sec
LBNE Beam Power @ 80-120 GeV	1.2	MW
LBNE Upgrade Potential @ 60-120 GeV	>2	MW

Proton Improvement Plan-II
Linac Technology Map



Section	Freq	Energy (MeV)	Cav/mag/CM	Type
RFQ	162.5	0.03-2.1		
HWR (β_{opt}=0.11)	162.5	2.1-11	8/8/1	HWR, solenoid
SSR1 (β_{opt}=0.22)	325	11-38	16/8/ 2	SSR, solenoid
SSR2 (β_{opt}=0.51)	325	38-177	35/21/7	SSR, solenoid
LB 650 (β_G=0.61)	650	177-480	30/20/5	5-cell elliptical, doublet
HB 650 (β_G=0.9)	650	480-800	24/10/4	5-cell elliptical, doublet

Proton Improvement Plan-II
Site Layout (provisional)



Proton Improvement Plan-II
Booster/Recycler/MI Requirements

- Booster
  - New injection girder to accept 800 MeV and enable transverse beam painting
  - Additional rf voltage (3-4 cavities) to support transition crossing manipulations
  - Upgrades to damper and collimator systems
- Recycler
  - RF cooling upgrade for operations at <1.2 sec cycle
  - Collimator upgrade
- Main Injector
  - RF power upgrade; new power amplifiers

Proton Improvement Plan-II
Cost Estimate

- Starting point is the Project X/Stage 1 estimate:
  - Estimates of major systems and components
    - M&S (FY13 dollars) and person-years
  - Fermilab (FY13) labor rates applied to effort
  - Overheads applied
  - Across the board 40% contingency
  - Original cost reviewed in March 2010
    - Updates to major component estimates since
  - Benchmark to SNS linac good to ~10%

Proton Improvement Plan-II Cost Estimate

- PIP-II estimate
  - Scope = Linac + beam transfer line + R&D + ProjMan + civil
    - LBNE target/horn system managed/funded by LBNE
    - Booster, Recycler, Main Injector upgrades managed through operating departments and funded as AIPs
  - Reutilize components from the PX/PIP-II development program
  - Estimate of cryogenic systems based on new concept for low duty factor operations*
  - Estimate of civil construction based on new siting*
  - Estimate of rf for lower duty factor operations (modest savings)
  - Efficient project schedule: 7 years from CD-0 to CD-4
  - Escalated to FY20 dollars

$\Rightarrow$ **DOE/TPC metric**

*Substantial savings from PX

Proton Improvement Plan-II Cost Estimate

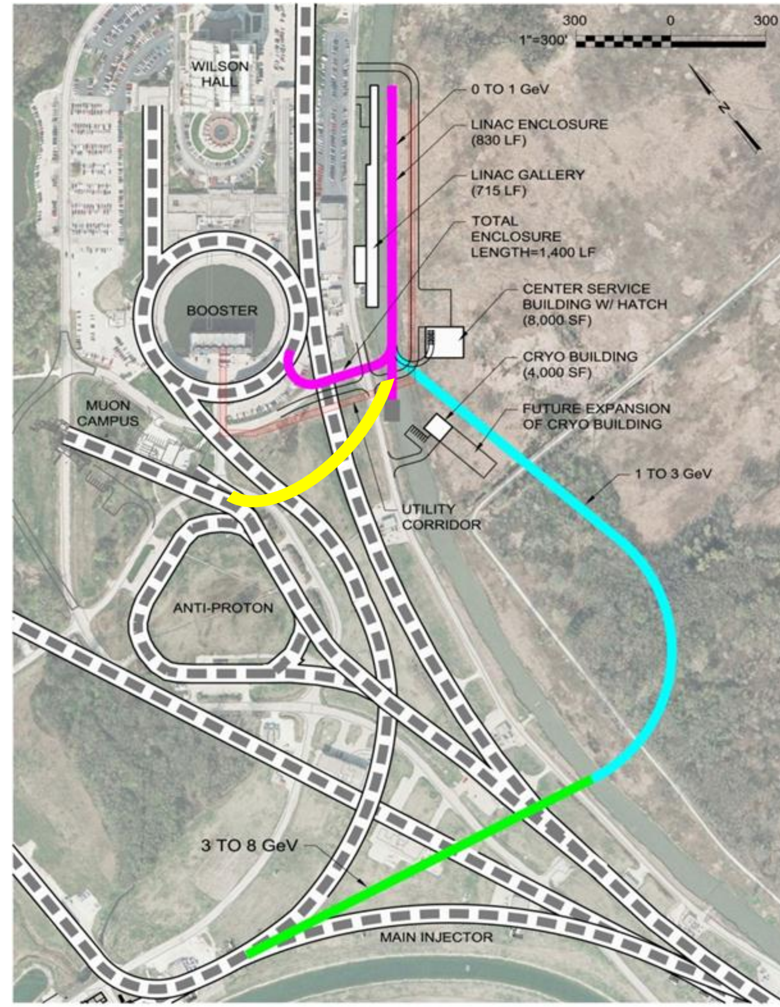
PIP-II Major Cost Component	Estimate ($M)
R&D	$27
Project Management	$26
Accelerating Cavities and Cryomodules	$70
RF Sources	$29
Cryogenic Systems (reuse existing CHL)	$14
Civil Construction	$66
Instrumentation	$12
Controls	$13
Mechanical Systems	$3
Electrical Systems	$2
Beam Transport	$5
Sub-total (direct, FY2013 dollars)	$266
Indirects, Contingency (40%), escalation (18%)	$276
TOTAL PROJECT COST (FY2020 Dollars)	**$542**

Proton Improvement Plan-II International Contributions

- Discussions at agency and laboratory levels indicate that an 800 MeV SC linac could attract significant in-kind contributions from India/Europe/Asia
  - SC accelerating structures
  - RF sources
  - Instrumentation
  - Magnets/power supplies
  - $150-200M (TPC metric) plausible
- Significant R&D collaboration for >5 years with India
  - Discussions at DOE-DAE level on potential Indian in-kind contributions

Flexible Platform for the Future

- PIP-II Inherent Capability
  - ~200 kW @ 800 MeV
- x10 Mu2e sensitivity
- 2 MW to LBNE
- Flexibility for future experiments



Fermilab

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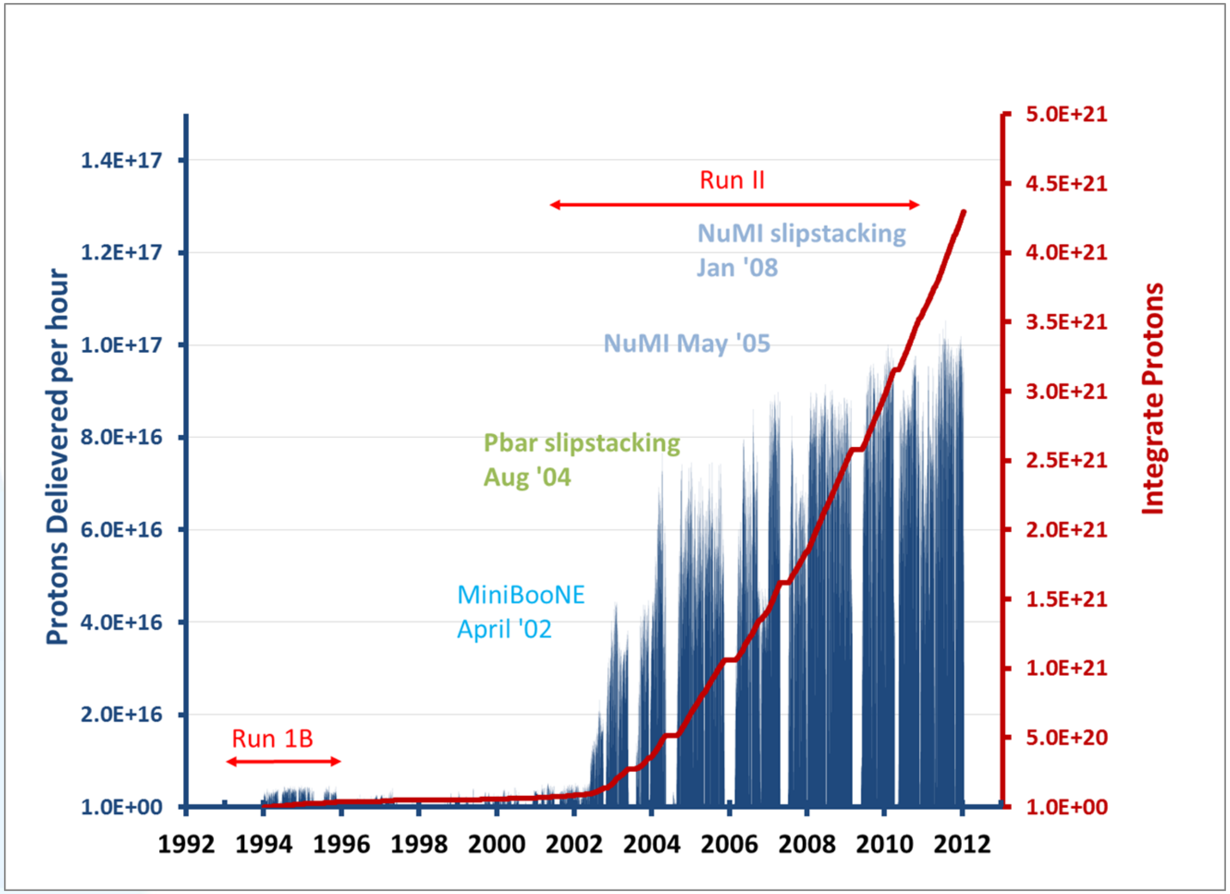
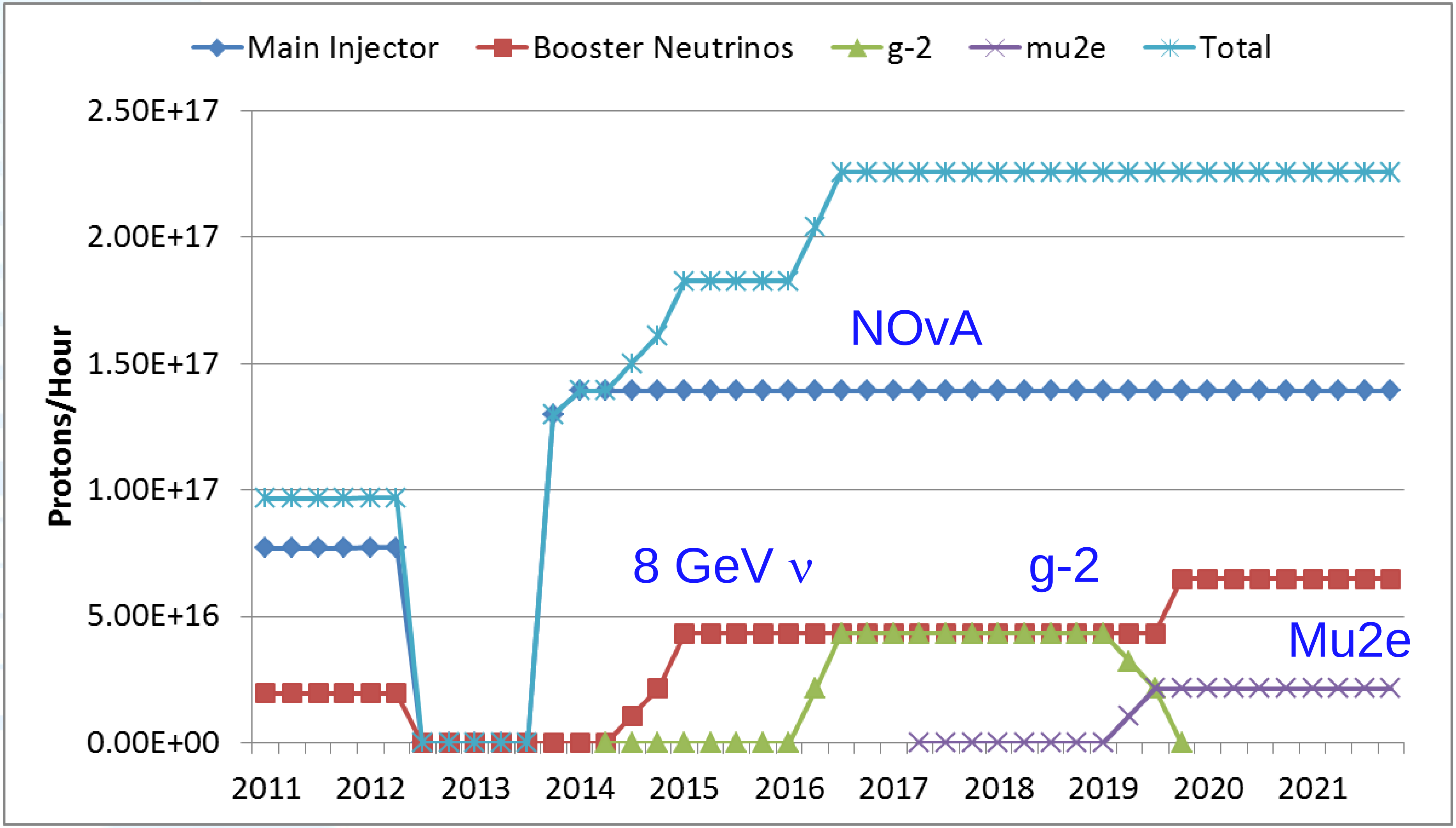
Backups

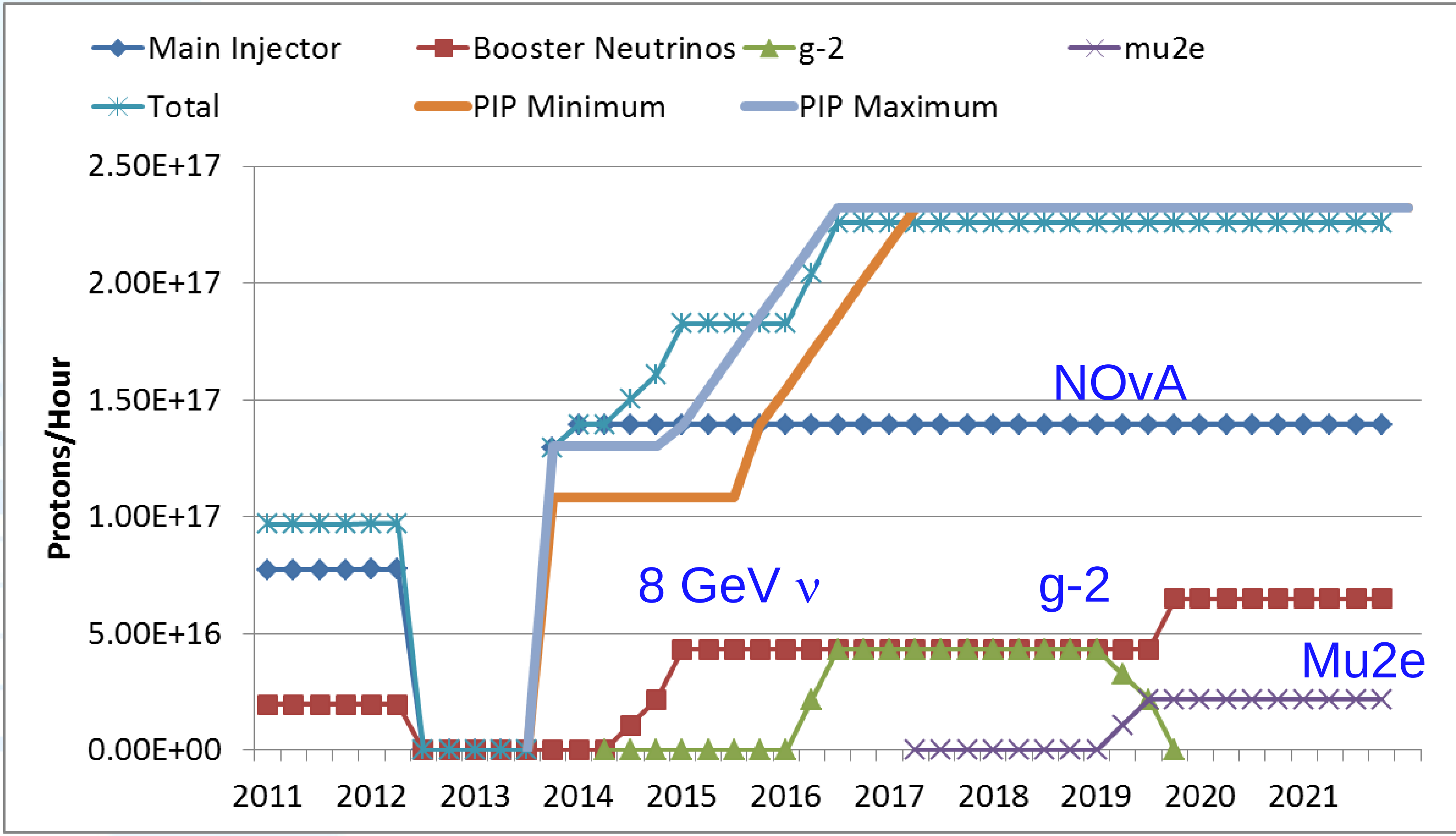
Proton Improvement Plan



Proton Demand



Proton Improvement Plan Projection



Fermilab

Proton Improvement Plan-II Options

- Plan A - Superconducting Linac
  - 800 MeV pulsed SC linac
  - Constructed from CW-capable accelerating modules
  - Operated initially at low duty factor
  - Sited in close proximity to Booster and to significant existing infrastructure
- Plan B - Afterburner
  - 400 MeV pulsed linac appended to existing 400 MeV linac
  - 805 MHz accelerating modules
  - Requires physical relocation of existing linac upstream ~50 m
  - ~1 year interruption to operations
  - Less expensive than Plan A

Proton Improvement Plan-II Pluses and Minuses

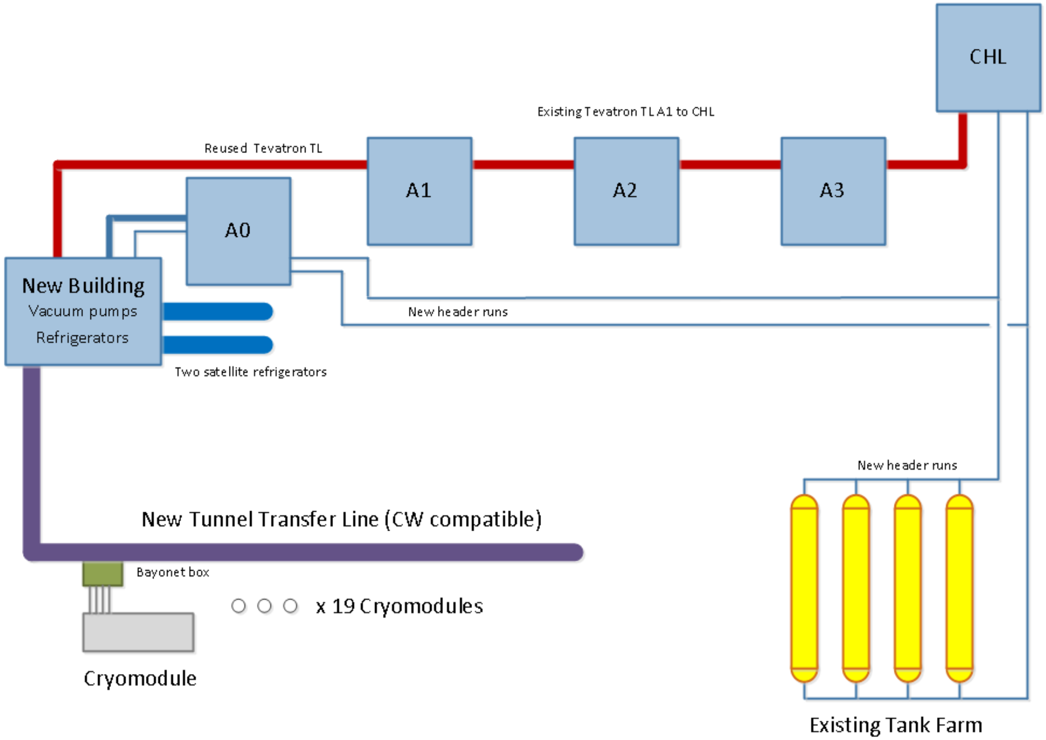
	Plan A: PIP-II	Plan B
Beam power to LBNE	1.2 MW	1.2 MW
Cost to DOE (FY2020 $M)	$350-400	$250
R&D aligned with efforts to date	**Y**	**N**
Upgradable to 2 MW to LBNE	Y	Y
High Duty Factor Capable	**Y**	**N**
Proton Driver for Muon Facility	Y	N
Upgrade paths utilize 1.3 GHz infrastructure & capabilities	Y	N
Retires significant reliability risks	**Y**	**N**
Interruption to operations	**~2 months**	**>12 months**
International contribution & collaboration	**Significant**	**Minimal**
Reutilization of existing infrastructure	Significant	Modest
Status of technical development/understanding	Advanced conceptual	Pre-conceptual

Linac Length Compare

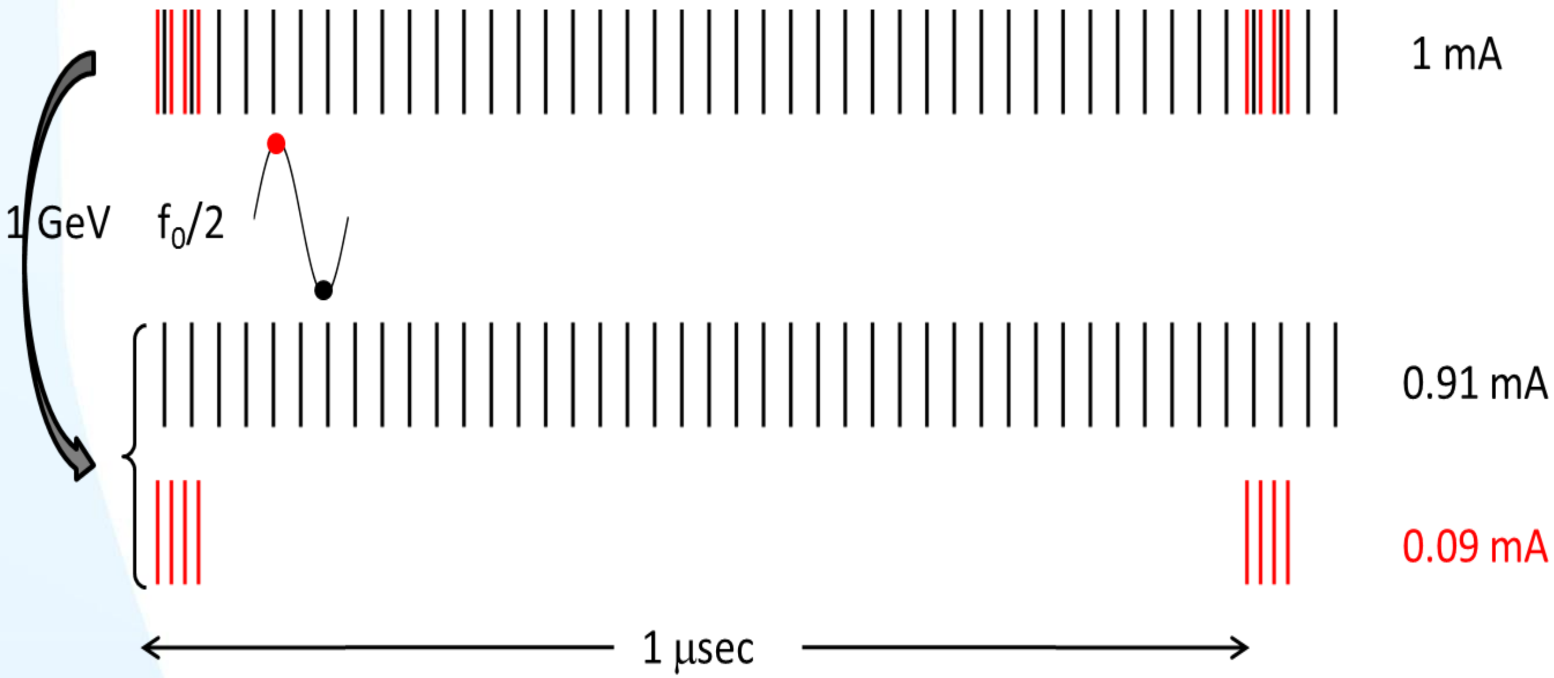
- Length of existing linac enclosure
  - 400 MeV: 145 m
- Length of PIP-II
  - 800 MeV: 190 m
  - 540 MeV: 145 m

Cryogenic System

- Required to support 5% cryogenic duty factor
  - Configuration capable of 10-15% with more pumping
  - 160 – 240 kW beam power at 800 MeV



Flexible Beam Formats



2+ MW

- Require 1.5×10^{14} particles from MI every 1.2 s @ 120 GeV
  - Every 0.6 sec @ 60 GeV
- Slip-stacking is not an option at these intensities
  - Need to box-car stack 6 x 2.5E13 protons in less than 0.6 sec $\Rightarrow$ >10 Hz rep-rate
  - Either Recycler (8 GeV) or MI (6-8 GeV)

2+ MW

- Booster is not capable of accelerating 2.5×10^{13} no matter how it is upgraded
  - Requires ~0.1% beam loss
  - High impedance
  - Transition crossing
  - Poor magnetic field quality
  - Poor vacuum
  - Inadequate shielding

⇒ *Achieving 2+ MW from Main Injector will require construction of a ≥1.5 GeV linac*

  - Can feed Main Injector via either a 6-8 GeV pulsed linac or rapid cycling synchrotron (RCS)

2+ MW to LBNE

Linac		
Particle Type	H^-	
Beam Kinetic Energy	8.0	GeV
Pulse rate	10	Hz
Pulse Width	6×4.3	msec
Particles per cycle to Recycler/MI	2.5×10^{13}	
Beam Power @ 8 GeV	320	kW
Main Injector/Recycler		
Beam Kinetic Energy (maximum)	60/120	GeV
Cycle time	0.6/1.2	sec
Particles per cycle	1.5×10^{14}	
Beam Power at 60-120 GeV	2400	kW

PX Reference Design Performance

CW Linac		
Particle Type	H^-	
Beam Kinetic Energy	3.0	GeV
Average Beam Current (@ 1 GeV)	2	mA
Average Beam Current (@ 3 GeV	1	mA
Beam Power to 1 GeV program	1000	kW
Beam Power to 3 GeV program	2870	kW
Pulsed Linac		
Particle Type	H^-	
Beam Kinetic Energy	8.0	GeV
Pulse rate	10	Hz
Pulse Width	6×4.3	msec
Particles per cycle to Recycler/MI	2.7×10^{13}	
Beam Power	340	kW
Beam Power to 8 GeV program	170	kW
Main Injector/Recycler		
Beam Kinetic Energy (maximum)	60/120	GeV
Cycle time	0.6/1.2	sec
Particles per cycle	1.5×10^{14}	
Beam Power at 120 GeV	2400	kW

simultaneous

R&D Program

- The goal is to mitigate risk: technical/cost/(schedule)
- Technical Risks
  - Front End (PXIE)
  - H- injection system
    - Booster in Stage 1, 2; Recycler in Stage 3
  - High Intensity Recycler/Main Injector operations
  - High Power targets
- Cost Risks
  - Superconducting rf
    - Cavities, cryomodules, rf sources – CW to long-pulse
    - Q0 is a primary cost driver in CW sections
- Nearly all elements are in play at PIP-II

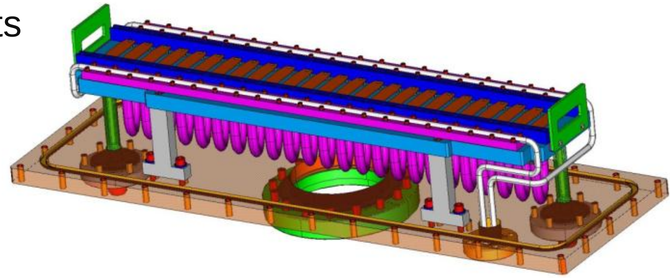
⇒ ***Goal is to be prepared for a construction start in 2018***

R&D Hardware Status

- PXIE
  - Ion source operational and characterized (LBNL→FNAL)
  - LEBT emittance scanner procurement initiated (SNS)
  - LEBT solenoids delivered (FNAL)
  - RFQ design complete; fabrication initiated (LBNL)
  - HWR cavity design complete and procurements initiated; CM design in process (ANL)
  - Nine qualified SSR1 cavities now in hand; CM design in process (FNAL)
  - Chopper proof-of-principle prototypes and driver development (FNAL)
  - Shielded enclosure under construction at CMTF
- SRF
  - Major progress on HWR, SSR1, 650 MHz ellipticals, and high Q0

Project X Injection Experiment PXIE

- PXIE is the centerpiece of the PX R&D program
  - Integrated systems test for front end components
    - Validate concept for Project X front end, thereby minimizing primary technical risk element within the Reference Design
    - Operate at full Project X design parameters

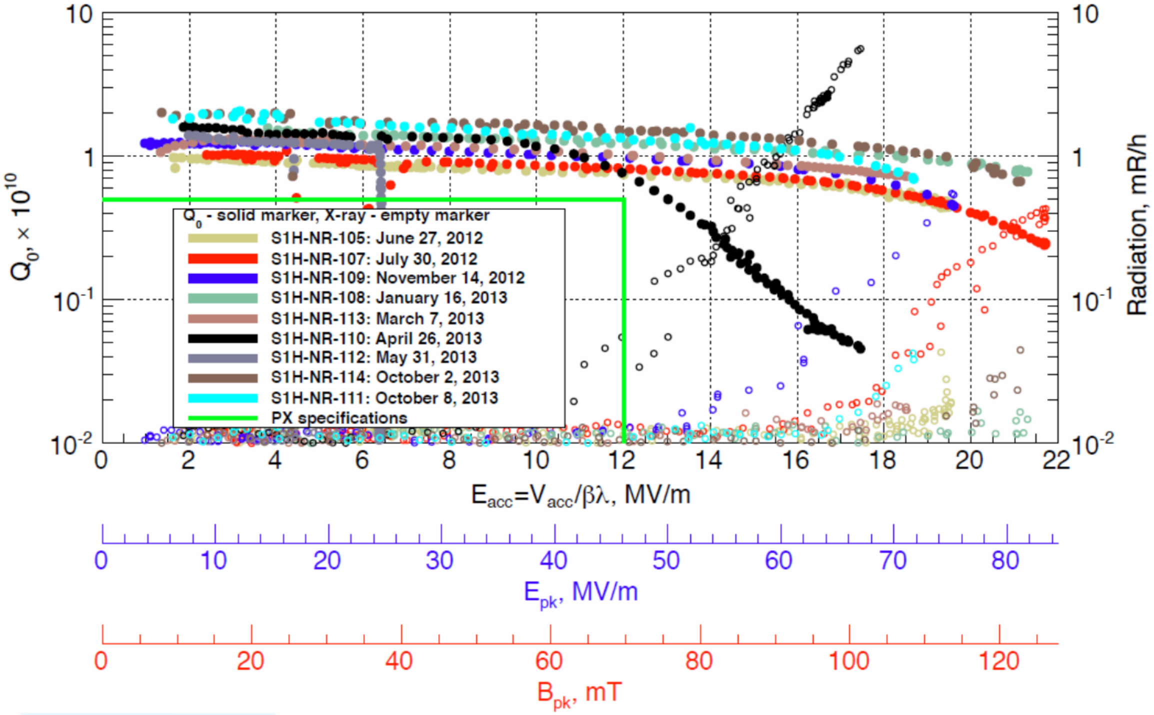


- Systems test goals
  - 1 mA average current with 80% chopping of beam delivered from RFQ
  - Efficient acceleration with minimal emittance dilution through ~30 MeV
- Utilizes components constructed to PX specifications wherever possible
  - Opportunity to re-utilize selected pieces of PXIE in Stage 1
- Collaboration between Fermilab, ANL, LBNL, SNS, India
- DOE Review of PXIE Program (January 2013)
  - "PXIE is a portion of a comprehensive Project X R&D program and…within the broader Project X R&D has the correct emphasis… PXIE allows FNAL to gain experience with an operational SRF hadron accelerator, an important step that will not occur any other way."

SRF Development Status

Cavity	Frequency	Cavity Type	Beta	Collaboration?	Cavity EM Design Complete	Cavity Mech Design Complete	Single Cell / Prototype Ordered	Full Cavity Prototype Received	Prototype Tested	Cavities for CM Ordered	Cavities for CM Received	Cavities for CM Tested	Cavities for CM Dressed	CM Cold Mass Design	CM Parts Ordered	# of CM Assembled	Est % complete
Half Wave Resonator (HWR)	162.5 MHz	1-HWR CW	0.11	ANL	yes	yes	yes	yes	not started	8	all parts	not started	not started	yes	WIP	not started	35
Single Spoke Resonator 1 (SSR1)	325 MHz	1-spoke CW	0.22	India	yes	yes	2	2	2	10	10	8	1	80%	WIP	not started	50
Single Spoke Resonator 2 (SSR2)	325 MHz	1-spoke CW	0.42	India	yes	yes	not started	not started	not started	not started	not started	not started	not started	not started	not started	not started	10
Low Energy 650 (LE 650)	650 MHz	5-cell CW	0.6	India, JLAB	yes	yes	2	not started	not started	not started	not started	not started	not started	not started	not started	not started	10
High Energy 650 (HE 650)	650 MHz	5-cell CW	0.9	India	yes	yes	5 of 10	4	not started	9	4	not started	not started	WIP	not started	not started	20
Pulsed Energy 1300 (ILC)	1300 MHz	9-cell pulsed	1.0	DESY, KEK	yes	yes	30	53	43	80	70	43	21	yes	5	2	90

SSR1 Cavity Performance

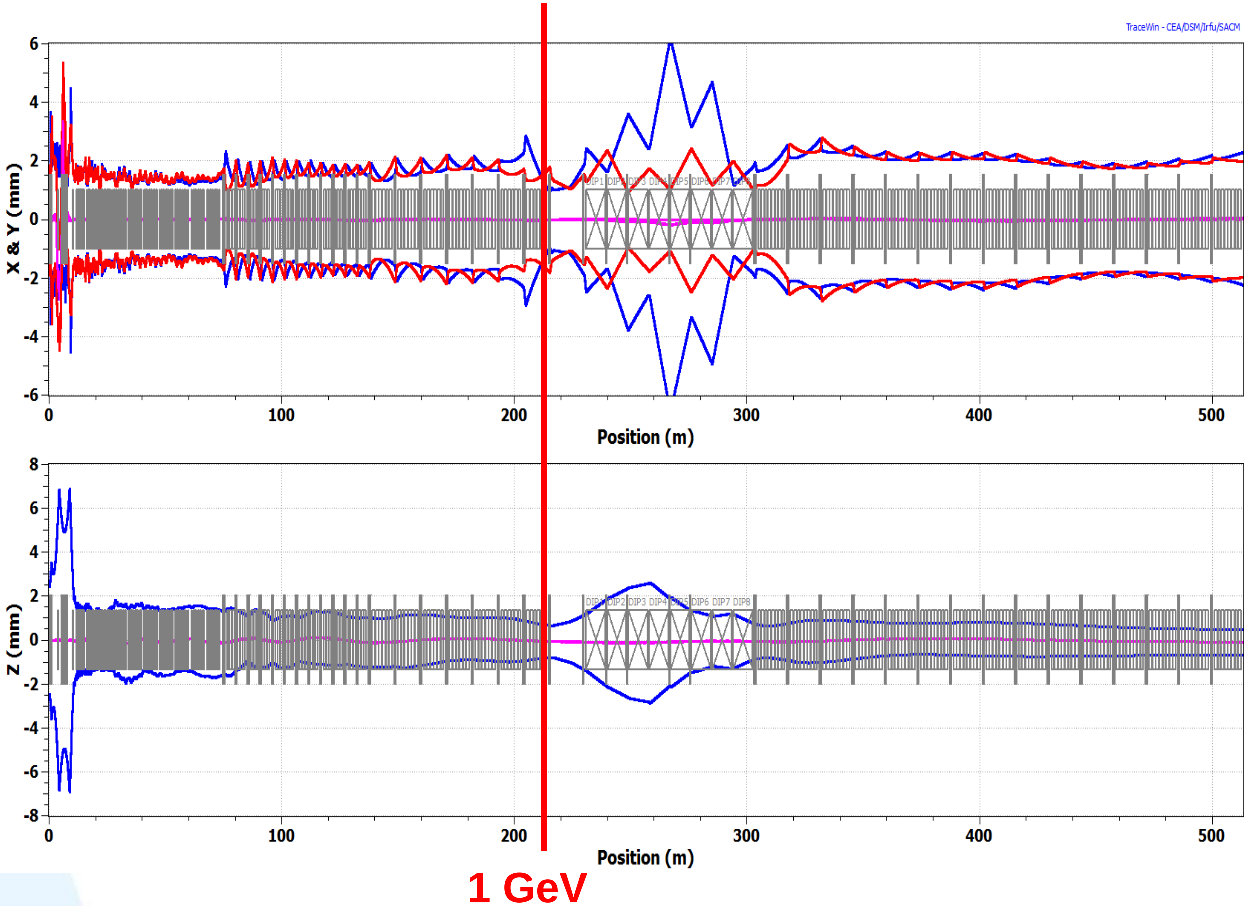


- 120-150 micron BCP and HPR at ANL/FNAL processing facility then 120 C bake
- Low FE depends on optimized nozzle design for effective HPR of surface

- Two previous SSR1 spoke resonators performed very well in bare cavity tests
- Above are the tests of 9 cavities from U.S. Vendor (Roark) production of 10 cavities
- Performance at 2 K is above requirements for Project X in both Q_0 and gradient

- Revised design of helium vessel and tuner are complete
- The first new SSR1 cavity is dressed.
- Measured df/dP = ~10 Hz/Torr

Linac Beam Dynamics



rms transverse beam envelopes (top), rms bunch length (bottom)

LBNE Target Facility @ 1.2 MW Development Needs

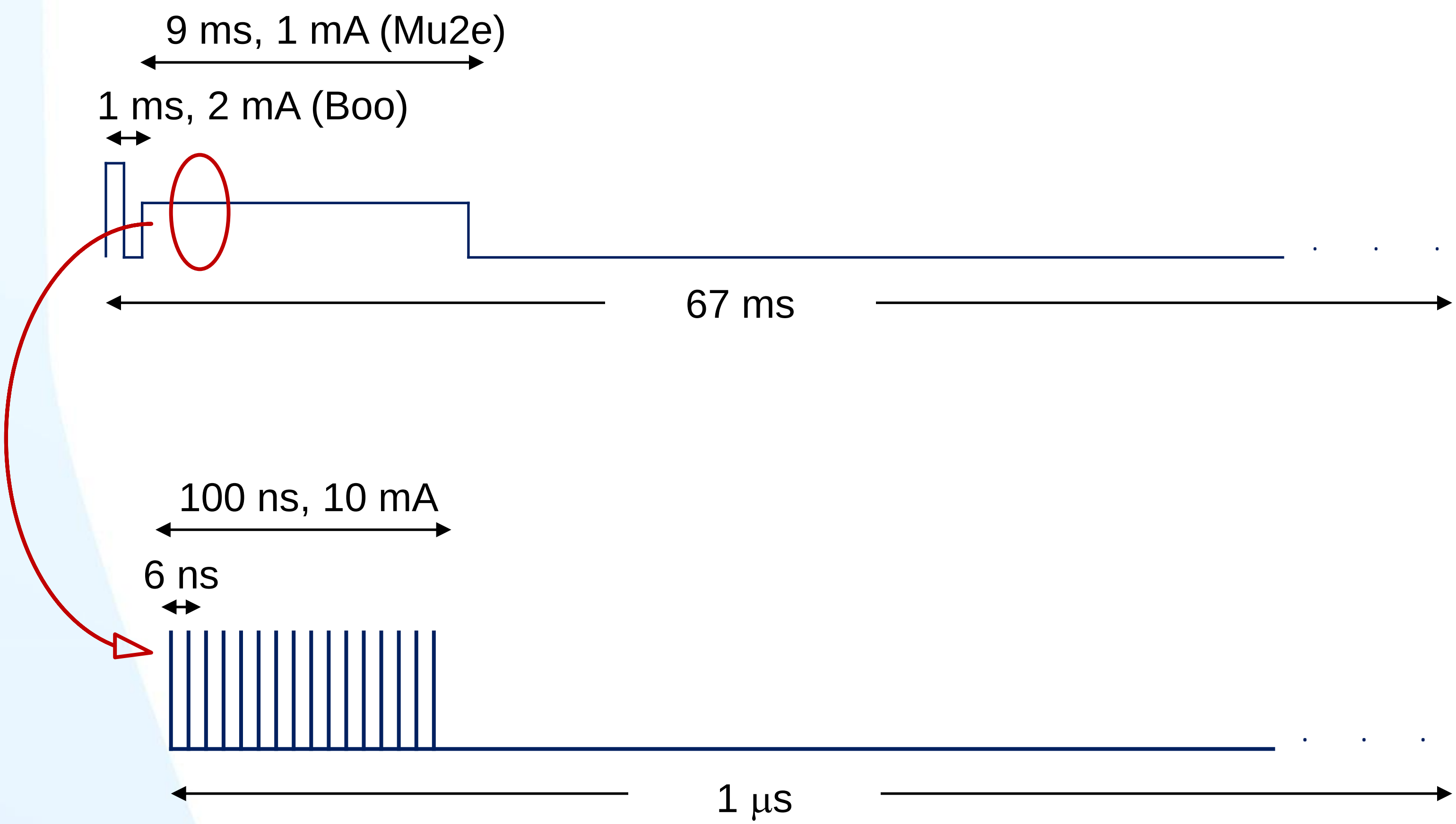
- The LBNE target needs to accept 1.2 MW beam power
- Development proceeding in the following areas:

System	Requirements
Primary Beam Window	Active cooling @2.3 MW; 1.2?
Target	Higher stress
Horns	Higher heat load and stress
Hadron Monitor	Radiation hardening, active cooling
Remote Handling	Additional short term storage facilities
Cooling Systems	Expanded capacity
Target Hall Shielding	0.25 m additional concrete shielding (top)

Mu2e w/ PIP-II

- Can operate PIP-II linac up to ~15% duty factor with cryogenic system as designed
- RF system as designed can support 2 mA (averaged over 1 μsec) at 15% duty factor
- RFQ can supply 10 mA
- MEBT chopper can provide arbitrary bunch patterns for separation at downstream end of linac.
- Mu2e Operations:
  - 10% micro-duty factor (100 ns $\times$ 1 MHz)
  - 13.5% macro-duty factor (9 ms $\times$ 15 Hz)
  - 10% $\times$ 13.5% $\times$ 10mA $\times$ 800 MeV = 108 kW

Mu2e w/PIP-II



Collaboration

- Organized as a "national project with international participation"
  - Fermilab as lead laboratory
- Collaboration MOUs for the RD&D phase :

National		IIFC
ANL	ORNL/SNS	BARC/Mumbai
BNL	PNNL*	IUAC/Delhi
Cornell	UTenn*	RRCAT/Indore
Fermilab	TJNAF	VECC/Kolkata
LBNL	SLAC	
MSU	ILC/ART	
NCSU*		

- *Recent additions bringing capabilities needed for experimental program development, in particular neutron targets and materials applications
- Ongoing collaboration/contacts with RAL/FETS (UK), ESS (Sweden), SPL (CERN), RISP (Korea), China/ADS